350/1 PUBL Publications
Sept 1958
350/1 Progress Report No. 3
359/359
350/1.6

INFRA·RED

BAUSCH & LOMB OPTICAL COMPANY · ROCHESTER 2, NEW YORK

September 8, 1958

NEAR-INFRARED TRANSMISSION FILTERS

INTRODUCTION: Two kinds of multilayer interference filters have been developed for the selective transmission of energy in the near-infrared. These are designated as "Band-Pass Filters" and "Long-Wavelength Pass Filters." Both types are efficient transmitters in the 1.4 to 4.5 micron region of the infrared, but are opaque in the visible.

Band-Pass Filters: "B. P." filters transmit a band of wavelengths sharply bounded on each side by an extended region of high reflectance and hence, low transmittance.

Long-Wavelength Pass Filters: "L. W. P." filters transmit radiation of all wavelengths above the cut-off region of the filter. The low wavelength transmission limit is determined by the infrared absorption of the substrate on which the filter coatings are deposited. Below the filter cut-off there is an extended background region of high reflectance which may merge with the absorption region of the filming materials.

CONSTRUCTION: The multilayer filter coatings are deposited on various substrates by the vacuum evaporation process with the thickness of the individual films comprising the coatings under accurate control. In common with filters of the thin film interference class, the wavelength position of the center of a transmission band, as well as the cut-off wavelength of a long wavelength pass filter are governed by the film thicknesses. Consequently, filters of given characteristics can be located as desired with respect to wavelength, within a range dictated only by practical limitations of the film thickness, and by absorption in the materials used.

RANGE: The range for the present series of filters is from 1.4 to 4.5 microns, with some exceptions for the narrower band pass types, as noted in the text below.

BAND PASS FILTERS

TERMINOLOGY: In the description to follow, certain terms will be used in identifying the filter characteristics and these are defined as follows:

Pass Band: The primary wavelength interval transmitted by the interference filter.

Background Region: The spectral region of low transmittance occurring on each side of the pass band.

Center Wavelength, λ_o : The wavelength in microns at the center of the pass band.

Half Width, H.W.: The spectral width of the pass band over which the transmittance is greater than one-half the maximum filter transmittance. Half width is expressed as a decimal fraction of λ_o, e.g. $.25\lambda_o$ for a B. P. filter, the H. W. of which is 25% of the center wavelength λ_o. This term is used also to designate the type of Band Pass Filter.

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Base Width, B. W.: The spectral width of the band at 3% transmittance for the $.25\lambda_o$ filter and at 1% transmittance for the others, expressed in all cases as a decimal fraction of λ_o .

Peak Transmittance, T_o: The maximum transmittance in the pass band of the filter. It is expressed as a percentage of the uncoated substrate transmittance T_s (See Table 1), due to the varying amounts of absorption in different substrate materials. The nominal peak transmittances tend to decrease with decreasing half widths.

Substrate Transmittance, T_s: Transmittance of the substrate materials before coating.

Free Filter Range, F. F. R.: The extent of the background region. This is taken to be the wavelength interval over which the background transmittance is below 3% for the $.25\lambda_o$ half width filter and below 1% for the others. It is expressed as a decimal fraction of λ_o. The free filter range factor on the lower side of the pass band is used to determine the location of the cut-off wavelength of auxiliary long wavelength pass filters where they are needed.

FILTER CHARACTERISTICS: Five different types of band pass filters have been developed. These are listed in Table I according to their half widths, by which each type may be designated.

TABLE I

Band Pass Filter Characteristics				
HW (Expressed as decimal fractions of λ_o)	BW	FFR	T_o/T_s*	Wavelength Range in microns
0.25	0.55	0.65 - 2.0	95%	1.4 - 5.0
0.125	0.27	0.68 - 1.9	90%	1.4 - 3.8
0.068	0.22	0.73 - 1.8	92%	1.4 - 4.0
0.045	0.17	0.73 - 1.8	70%	1.7 - 3.8
0.015	0.09	0.78 - 1.7	45%	1.75 - 3.8

*Below 1.8 microns, the filter transmittances are less than the nominal values.

Range: The wavelength range throughout which it is practical to manufacture the filters differs slightly among the different types. This information is given in the last column of Table I.

Tolerances: The standard manufacturing tolerance on the location of the filter pass bands is $\pm$3% of a prescribed wavelength. Figures 4 through 13 are Transmittance curves of typical band pass filters of the five types. Each type is represented by two different filters, with pass bands at different wavelengths.

Leakage: Auxiliary filters and special substrates are often required to eliminate leakage of undesired radiation beyond the limits of the free filter range. The sections on auxiliary filters, substrate and composite filters should be consulted.

Examples: Figure 1 is a measured spectrophotometric transmittance curve of a representative band pass filter centered at 2.45 microns. Figure 2 is the measured spectrophotometric transmittance curve of a representative long wavelength pass filter with its cut-off at 1.8 microns. Figure 3 is the transmittance curve of a band pass filter superimposed on a long wavelength pass filter to produce a filter combination with an extended free filter range. Figures 4 through 13 are transmittance curves of typical Band Pass Filters of the 5 types.

Oblique Incidence: The optical data on filters as given refer to normally incident light. Oblique incidence of the light shifts the transmittance band towards the shorter wavelengths. When they are used at an angle of 45 degrees, this displacement is approximately 5% of λ_o for the .25 λ_o and .045 λ_o filters, and 11% for the .015 λ_o and .068 λ_o filters. The .125 λ_o filter is not recommended for use on other than normal incidence, unless especially designed for the purpose.

LONG WAVELENGTH PASS FILTERS

TERMINOLOGY: In order to express the characteristics of this type of filter, the following terminology has been adopted:

Cut-off Wavelength, λ_c : The wavelength at which transmittance is 5% of maximum.

Slope: The rate at which transmittance increases from the cut-off wavelength λ_c to the wavelength λ_c' where 80% of maximum transmittance occurs. This is given by the wavelength difference $\lambda_c' - \lambda_c$ expressed as a decimal fraction of λ_c . For example the filter of Figure 2 has a cut-off slope of 0.09 λ_c .

Free Filter Range, F.F.R.: The region of the filter from λ_c to the point at shorter wavelengths where the transmittance rises to 1%. Below the cut-off wavelength λ_c , there is a background region of very high reflectance and, accordingly, low transmittance. The lower wavelength limit of the free filter range is listed in the second column of Table II as a decimal fraction of the cut-off wavelength λ_c .

FILTER CHARACTERISTICS: Three long wavelength pass filter types have been developed, their data being listed in Table II. These differ in their cut-off slopes, by which they are designated.

TABLE II

Long Wavelength Pass Filter Characteristics			
Slope (Expressed as decimal fractions of λ_c)	FFR	T_o/T_s*	λ_c Range in microns
0.12	0.52	86%	1.35 - 5.0
0.09	0.51	86%	1.35 - 5.0
0.05	0.50	86%	1.35 - 5.0

*The maximum transmittance of the filters generally occurs near the cut-off and may exceed 95% of the uncoated substrate transmittance. The transmitting region does not extend smoothly toward the longer wavelengths, but contains small secondary interference maxima and minima. At any wavelength in this region, if above 1.8 microns, filter transmittances of 86% or more of the uncoated substrate transmittance can be expected.

Range: Each filter type can be made with its cut-off wavelength located anywhere in the interval of 1.35 to 5.0 microns.

Tolerance: The cut-off wavelengths can be prescribed within a ±3% manufacturing tolerance anywhere in the wavelength interval of 1.45 to 5.0 microns.

Leakage: Auxiliary filters and special substrates are often required to eliminate leakage of undesired radiation beyond the limits of the free filter range. This subject is treated in the sections on auxiliary filters, composite filters and substrate filters.

Examples: Figures 14, 15, and 16 are transmittance curves of typical long wavelength pass filters of each of the three types.

Oblique Incidence: At oblique incidence, the transmission curve of a long wavelength pass filter is shifted towards a shorter wavelength. This shift is about 3% for a 15 degree angle of incidence, 8% for 30 degrees and 15% for 45 degrees. At angles greater than 30 degrees an irregularity appears in the cut-off slope.

AUXILIARY FILTERS

Because of their high transmittances, two or more filters may be used efficiently in series. This is often of considerable advantage by permitting an extension of the free filter range with appropriate combinations of filters. The background or rejection region of a certain filter may not extend over a sufficiently wide wavelength span to allow the filter to be used by itself in a particular application. To prevent leakage of unwanted radiation beyond the limits of its free filter range, it then becomes necessary to supplement the primary filter with one or more auxiliary filters.

Long wavelength pass filters are used as auxiliaries when the free filter range of a band pass filter must be extended toward shorter wavelengths. Figure 3 is the transmittance curve obtained by superimposing a band pass filter and a long wavelength pass filter, similar to those of Figures 1 and 2. As a second example, Figure 17 is a transmittance curve of an $0.045\lambda_0$ half width band pass filter in series with an auxiliary long wavelength pass filter having its cut-off wavelength at 2.6 microns.

With proper matching, a band pass and a single long wavelength pass auxiliary filter in series can be made to reject all radiation between the pass band of center wavelength λ_0 and a short wave limit at about $.35\lambda_0$. If this limit falls below 1 micron, the free filter range continues indefinitely toward shorter wavelengths because of absorption in the filter materials. If it falls above 1 micron, the free filter range of the auxiliary must be extended.

The free filter range of a long wavelength pass filter can be extended by superimposing a second long wavelength pass filter having its cut-off at a shorter wavelength. Figure 18 illustrates this for the case of a primary long wavelength pass filter with its cut-off near 2.44 microns. This filter has been combined in series with a second long wavelength pass filter having its cut-off at 1.5 microns. Long wavelength pass filters above 2.0 microns must have auxiliary filters to avoid radiation leakage at wavelengths below the short wavelength limit of their free filter range.

Beyond the long wavelength limit of the free filter range of any of the band pass filters the transmittance can be reduced to zero either by absorption in its substrate or by the insertion of an additional plate of absorbing material as will be discussed in the section below on Substrates.

COMPOSITE FILTERS

Two filters can be deposited on a single substrate one on each side, thereby forming a composite filter. This procedure is advisable:

1. When the region of interest occurs at wavelengths where the substrate is absorbing, and the total thickness of the substrate material in the path must be held to a minimum.

2. When two auxiliaries are necessary to extend the free filter range sufficiently, and it is a convenience to combine them on one substrate.

3. When it is desired to have a "self-sufficient" filter, the primary and its auxiliary being on the same substrate.

Figure 19 shows a typical composite long wavelength pass filter.

SUBSTRATES

The common substrate materials for this filter series are:

1. Microscope cover-glass slip
2. Bausch & Lomb Type RIR12 Calcium Aluminate Glass
3. Bausch & Lomb IR-1 Glass
4. Calcium Fluoride

In most cases, the filters are deposited on 25mm diameter microscope cover-glass slips of 0.13 to 0.17mm thickness. The useful spectral range of this thin glass extends out to approximately 4.5 microns before the transmittance falls below 70% due to absorption. The transmittance at wavelengths shorter than 4.3 microns exceeds 80%.

The physical properties of sapphire severely limit the wavelength range of satisfactory filter coatings which can be deposited on it.

Bausch & Lomb IR-1 Glass, magnesium oxide and lithium fluoride have special advantages in limiting the transmission at long wavelengths.

Except for a narrow absorption band at 2.7 microns, mica is fully transparent to 5 microns in a thickness of .05mm. The transmission curve does, however, display interference maxima and minima, and the difference in transmittance between them may amount to 10%.

Fused quartz is useful on occasion when the substrate must be thick for mechanical strength and yet have full transmission to about 3.4 microns.

Although arsenic trisulfide glass, silicon and germanium take the filter coatings satisfactorily, the transmittances of the resulting filters are below those of the other substrates mentioned. This is a result of the very high refractive indices of the former, for which the filter coatings were not designed.

Figure 20 gives the spectrophotometric transmittance curves of the four common substrate materials in the thicknesses indicated.

The natural infrared absorption cut-off toward long wavelengths of the substrate materials can often be used to advantage in the design of a filter. For example, it may be desired to definitely limit the region of transmission of a long wavelength pass filter. The filter coating itself transmits to beyond 15 microns. By proper choice of substrate material and thickness, the transmission can be terminated at some shorter wavelength. In effect, this results in a band pass filter which can be made much wider than the $.25\lambda_o$ band pass filter, the widest in the series of band pass filters which is offered.

The materials in Table III in the proper thicknesses are suggested as substrates possessing useful long wavelength absorption cut-offs. They have been selected on the basis of experience as suitable for the deposition of the filter coatings and for satis-

factory workability to the thicknesses required, in addition to having relatively well defined cut-offs. Figure 21 illustrates this table.

TABLE III

Substrates for Controlled Long Wavelength Cut-Offs		
Material	Thickness	Cut-off Wavelength
Bausch & Lomb IR-1 Glass	0.5mm	5.3 microns
B&L Calcium Aluminate RIR-12 Glass	2.0mm	6.25 microns
B&L Calcium Aluminate RIR-12 Glass	0.5mm	6.8 microns
Lithium Fluoride	5.0mm	8.2 microns
Magnesium Oxide	3.0mm	9.6 microns
Calcium Fluoride	5.0mm	11.5 microns
Magnesium Oxide	0.5mm	11.6 microns
Calcium Fluoride	0.5mm	14.5 microns

GENERAL INFORMATION

SIZE: The most common size for the filters of this series is 25mm diameter with a free aperture of the coating of about 23mm or more. In some instances diameters up to $3\frac{1}{2}$" may be supplied. The availability of substrate material may limit the maximum diameter. For example, magnesium oxide crystals, large enough to work into plates more than 1" diameter are rare. Filters smaller than 25mm can also be furnished, as well as filters of shapes other than round.

MAINTENANCE: Filter coatings on the substrate are exposed and have no protective covering. They must not be subjected to rough usage. If cleaning is necessary, a soft cloth may be used, dampened with water-free pure acetone when necessary. Mechanical failure of the coating may result if heated above 100 degrees C.

AVAILABILITY: In the engineering development of these filters, moderate quantities of both band pass and long wavelength pass filters have been produced on 1" cover-glass slip. If your specifications permit their use, delivery can be made within a period of a week to ten days after receipt of order. All specifications are examined with this possibility in mind. Quantities are limited and are subject to prior sale.

When the available inventory is not suited for this purpose, filters are made to order as engineering specials. It is recommended that specifications, requested below on "How to Order," be carefully studied with the object of giving as wide a range of specifications as possible.

PRICE: Because of the great variety of possible combinations, prices are not quoted in this report. If available inventory on 1" cover-glass slip can be utilized, a substantial saving in the price of the filter can be realized. We welcome the opportunity of quoting on your specific needs.

HOW TO ORDER: In requesting your quotation or ordering, the following information is necessary and will permit us to give you a prompt, complete quotation:

B.P. BAND PASS FILTERS (from Table I)

(1) Half Width Designation (column 1 - Table I)
(2) Center Wavelength λ_o *
(3) Substrate+
(4) Free Filter Range**(column 3 - Table I)
(5) Tolerance on λ_o ($\pm$3% unless otherwise stated)
(6) Dimensions+
(7) Quantity

L.W.P., LONG WAVELENGTH PASS FILTERS (from Table II)

(1) Cut-off Wavelength λ_c *
(2) Slope (column 1 - Table II)
(3) Substrate+
(4) Free Filter Range**(column 2 - Table II)
(5) Tolerance on λ_c (+3% unless otherwise stated)
(6) Dimensions+
(7) Quantity

*When specifying either center wavelength for band pass filters or cut-off wavelength for long wavelength pass filters, we suggest that the range be made as broad as possible to permit the use of available filters wherever these can be offered.

**Please also indicate whether you wish us to offer auxiliary filters where needed, and whether they are to be composite with the primary filter. Otherwise, auxiliary filters will be offered as separate items. Generally speaking, the composite filter construction is somewhat more costly than the use of filters in series.

+ Unless otherwise stated, substrate material will be 25mm diameter, No. 1 microscope cover-glass slip.

Prices depend on quantity, substrate materials and dimensions, special wavelength tolerances, etc.

Please address your inquiries to Bausch & Lomb Optical Co., Defense Contract Department, Rochester 2, New York.

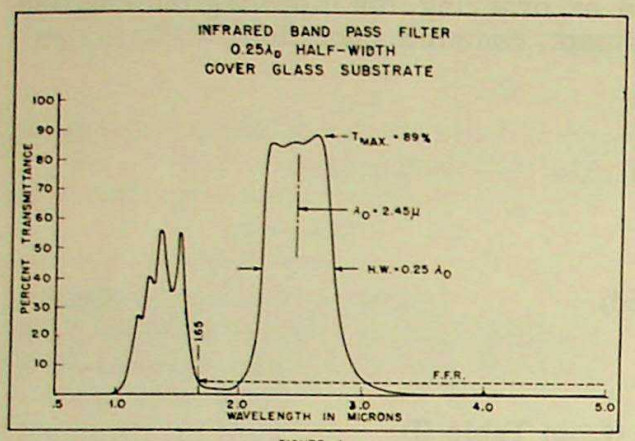


FIGURE 1

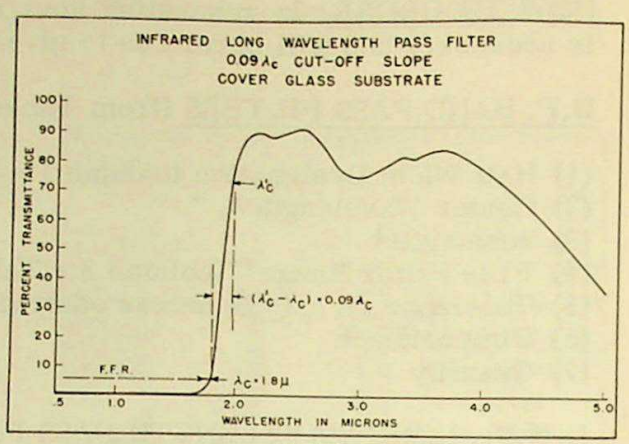


FIGURE 2

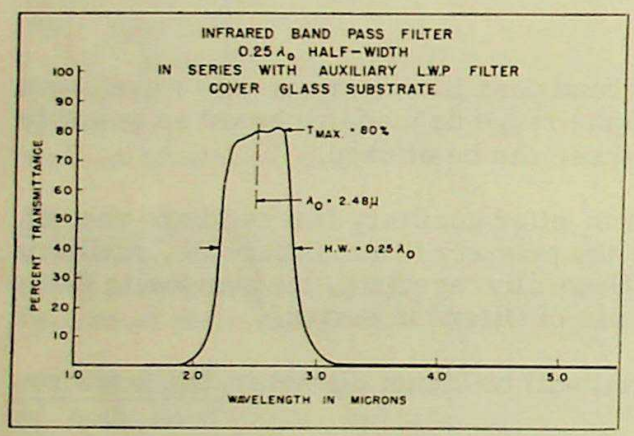


FIGURE 3

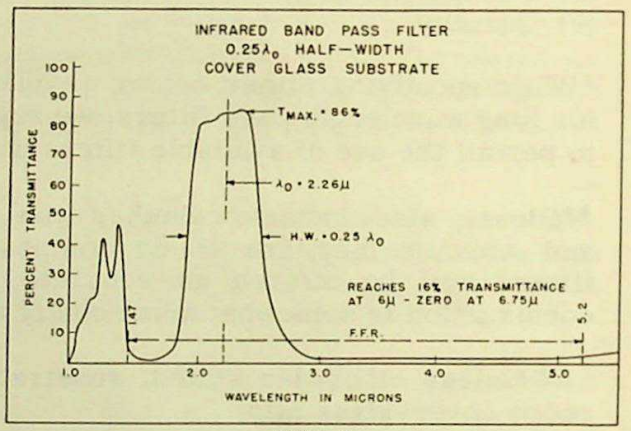


FIGURE 4

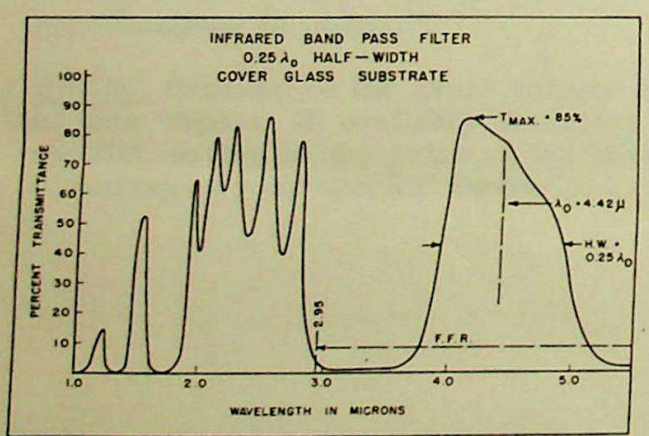


FIGURE 5

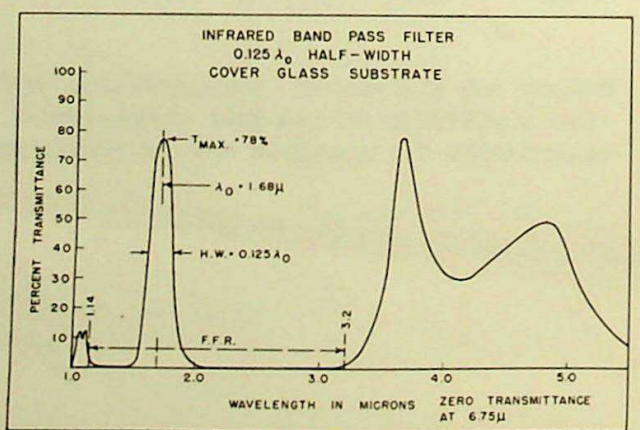


FIGURE 6

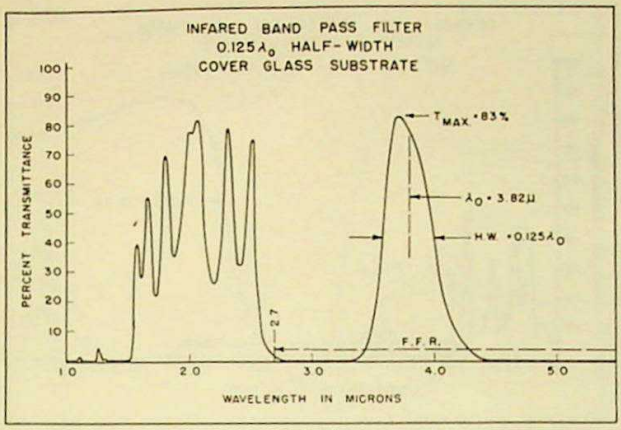


FIGURE 7

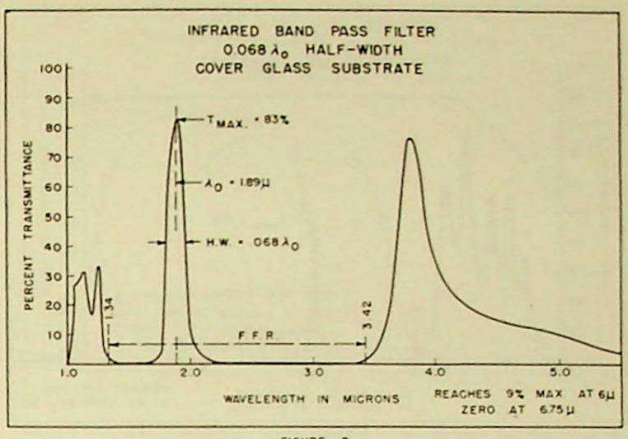


FIGURE 8

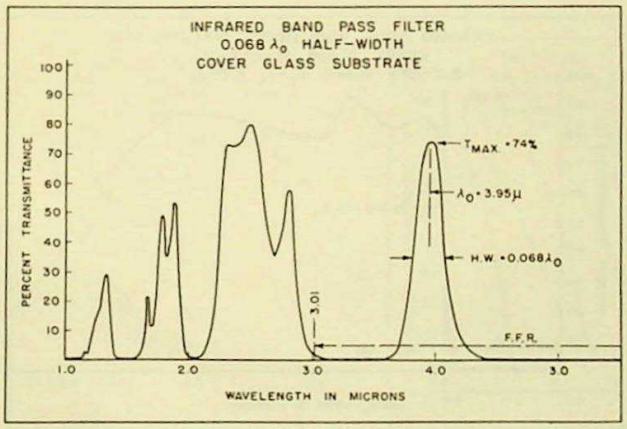


FIGURE 9

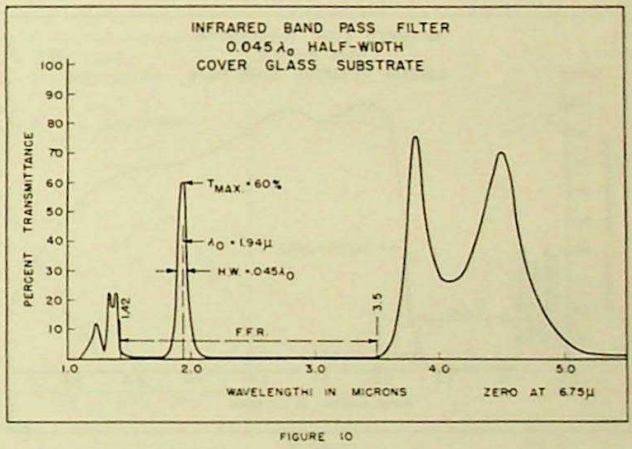


FIGURE 10

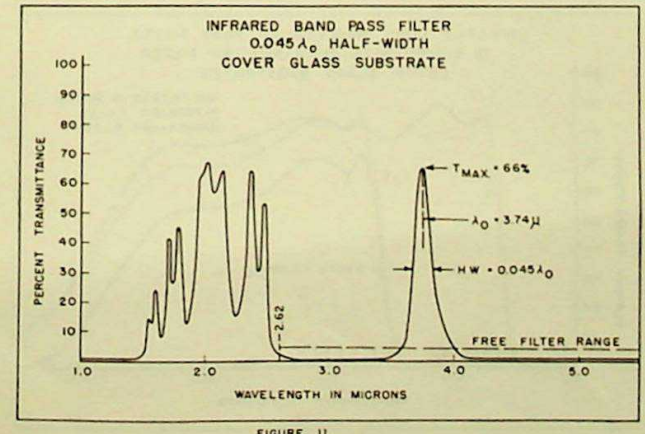


FIGURE 11

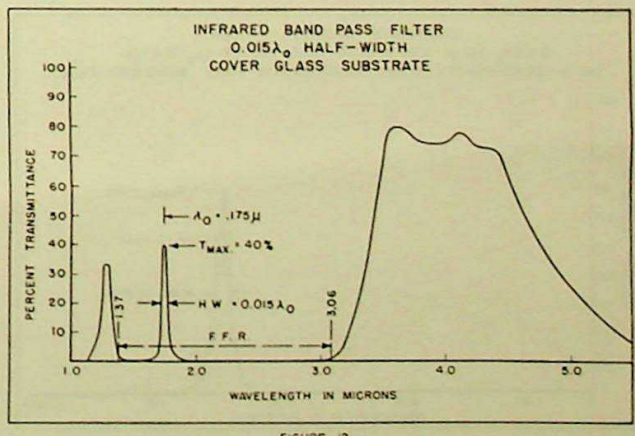
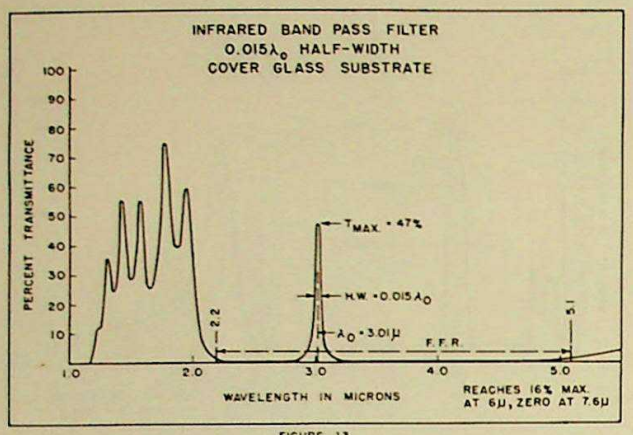


FIGURE 12



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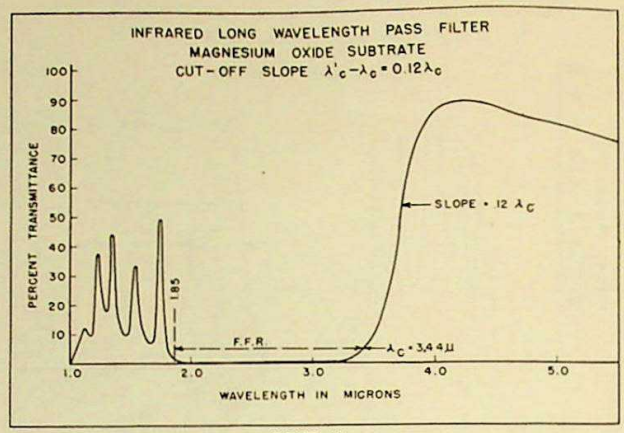

FIGURE 14

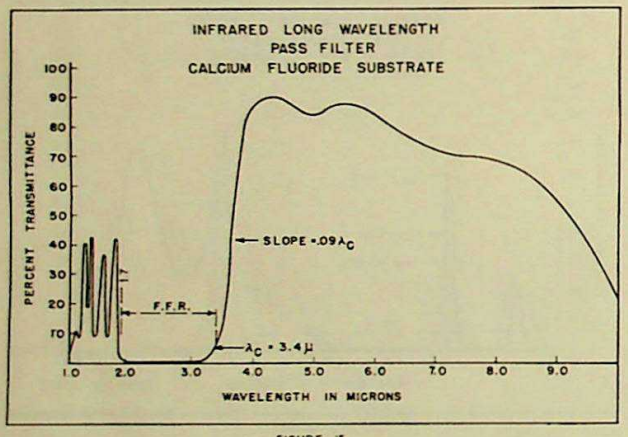

FIGURE 15

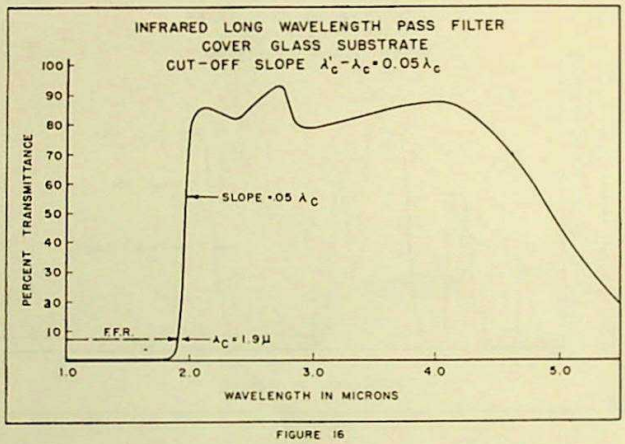

FIGURE 16

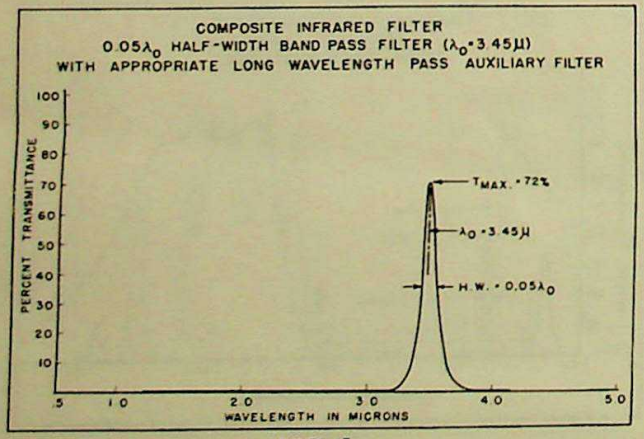
COMPOSITE INFRARED FILTER
0.05λ0 HALF-WIDTH BAND PASS FILTER (λ0 = 3.45μ)
WITH APPROPRIATE LONG WAVELENGTH PASS AUXILIARY FILTER
PERCENT TRANSMITTANCE
WAVELENGTH IN MICRONS
TMAX. = 72%
λ0 = 3.45μ
H.W. = 0.05λ0

FIGURE 17

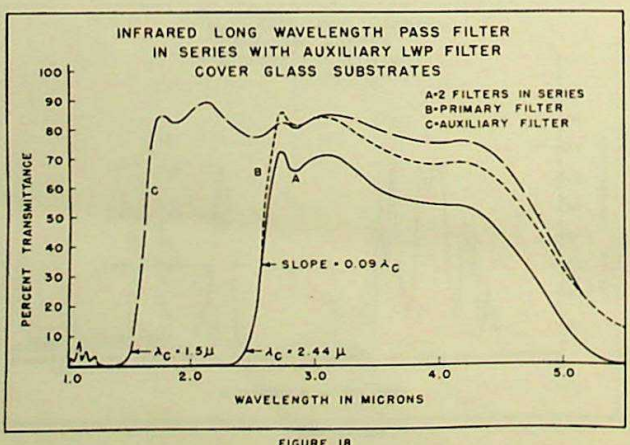

FIGURE 18

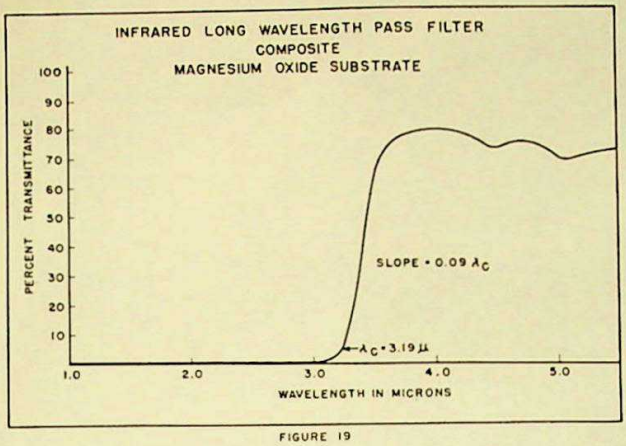

FIGURE 19

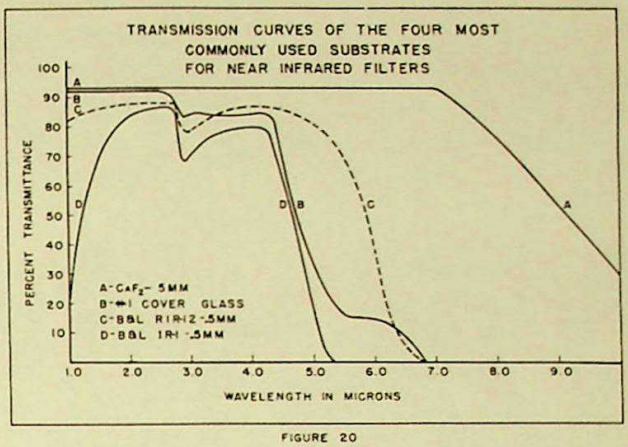

FIGURE 20

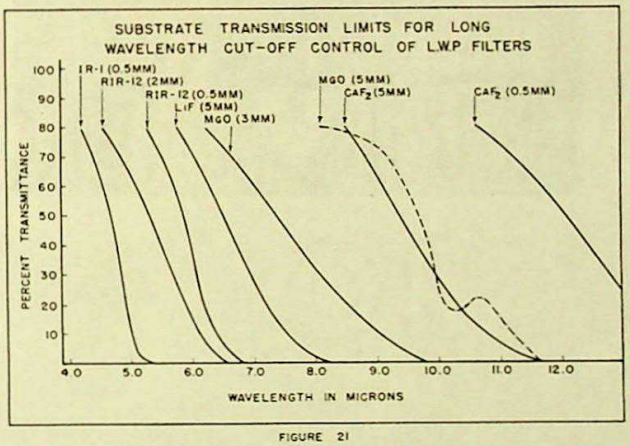

FIGURE 21

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